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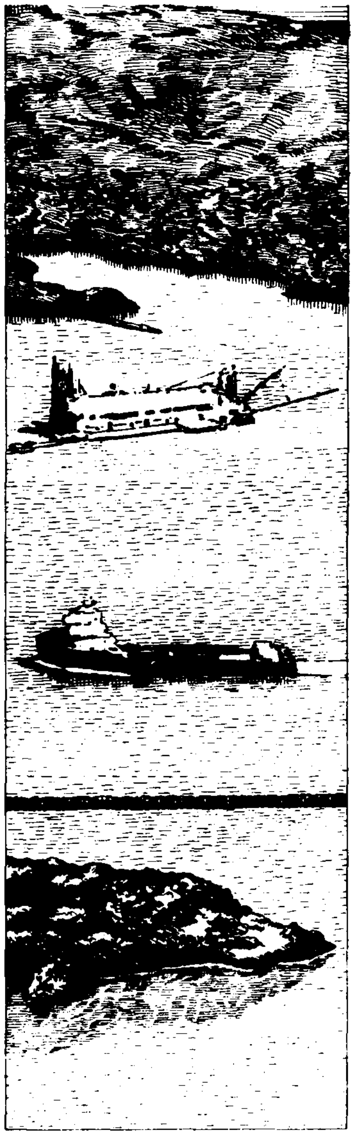

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DREDGING RESEARCH PROGRAM

TECHNICAL REPORT DRP-92-4

LABORATORY TESTING OF METHODS TO INCREASE HOPPER DREDGE PAYLOADS: MODEL HOPPER BIN FACILITY AND CENTRIFUGAL SOLIDS CONCENTRATOR

by

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Area 2 - Material Properties Related to Navigation and Dredging

Area 3 - Dredge Plant Equipment and Systems Processes

Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems

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It is common practice to fill beyond overflow on dredge hoppers and scows to achieve load gains. However, some of the US Army Corps of Engineers Districts do not permit overflow due to actual or perceived environmental or economic reasons. It is generally not known whether overflowing is beneficial in increasing the hopper payload in fine-grained sediments (silt and clay size), although some studies have indicated a minimal increase in hopper loads when filled to overflowing. Under the Dredging Research Program (DRP) Work Unit, "Technology for Monitoring and Increasing Dredge Payload for Fine-Grained Sediments," several experimental methods were investigated to determine their effect on increasing the payload of fine-grained dredged material.

Several devices were tested in a scale model hopper constructed at the US Army Engineer Waterways Experiment Station Hydraulics Laboratory. These devices included three types of hydrocyclones (centrifugal separators), various

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diffuser designs, and different arrays of internally mounted inclined plates. A solids concentrator device was also evaluated for increasing the load of fine sediments in the model hopper.

This report presents the description and method of the testing programs and the study findings. The inclined plate and solids concentrator devices demonstrated some level of success when tested with silt-sized materials (particle size 10 to 63 microns). The inclined plate method was the most successful for increasing payload in the model hopper; however, prototype use of this technique could substantially increase the weight of a hopper dredge unless a lightweight version is developed. The technique may have economic benefits in separating sediments out of the effluent of a confined disposal site, or when specialized separation techniques might be required in the cleanup of contaminated sediments.

PREFACE

This study was conducted by the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES) during the period April 1989 to October 1990. The study was sponsored by the Headquarters, US Army Corps of Engineers (HQUSACE), as a part of the Dredging Research Program (DRP), Work Unit 32475, "Technology for Monitoring and Increasing Dredge Payload for Fine-Grained Sediments," managed by the WES Coastal Engineering Research Center (CERC). HQUSACE Technical Monitor for DRP Technical Area 3, Dredge Plant Equipment and Systems Processes, was Mr. Gerald Greener. Mr. Robert H. Campbell was Chief Technical Monitor.

This report was prepared by Messrs. Stephen C. Scott, Walter Pankow, and Thad C. Pratt of Estuaries Division (ED), HL. The work was performed by Messrs. Scott, Pratt, and Dr. J. Machemehl of Texas A&M University, College Station, TX. Dr. Machemehl, employed under an Intergovernmental Personnel Agreement, assisted with the initial testing. Mr. Larry Caviness, ED, assisted with laboratory analysis. Mr. Leo Keostler, Instrumentation Services Division, WES, assisted with the instrumentation design and installation. Technical review was performed by Mr. Allen M. Teeter and other ED staff. The solids concentrator tests were conducted under contract by the Advanced Resource Development Corporation (ARD), Columbia, MD, with Dr. E. B. Silverman the principal investigator.

The study was conducted under the general supervision of Mr. Frank A. Herrmann, Jr., Director, HL; Mr. Richard A. Sager, Assistant Director, HL; and Mr. William H. McAnally, Jr., Chief, ED. Mr. William H. Martin, ED, was the Manager of DRP Technical Area 3. Principal Investigators were Mr. Teeter and Ms. Pankow. Program Manager of the DRP was Mr. E. Clark McNair, Jr., CERC. Dr. Lynn Hales, CERC, was Assistant Program Manager. This report was edited by Ms. Marsha C. Gay of the WES Information Technology Laboratory.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

For further information on this report or on the Dredging Research Program, please contact Mr. E. Clark McNair, Jr., Program Manager, at (601) 634-2070.

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SUMMARY

Within the Dredging Research Program (DRP) Work Unit, "Technology for Monitoring and Increasing Dredge Payload for Fine-Grained Sediments," several types of devices were laboratory tested to determine their effect on increasing the loads of fine-grained dredged materials.

Several devices were tested in a scale model hopper constructed at the Hydraulics Laboratory (HL), US Army Engineer Waterways Experiment Station. The model hopper was used to test various devices and techniques designed to increase the payload of fine-grained sediments typically found in dredge hoppers. The devices tested included three types of hydrocyclones (centrifugal separators), various designs and configurations of diffusers, and different arrays of internal inclined plates. The hydrocyclone and diffuser tests indicated a limited success in increasing the amount of sediments separated out of a clay slurry. The most successful device tested was a series of inclined plates mounted inside the model hopper. Although the inclined plate method indicated up to a 50 percent increase in solids retention for low-density silt slurries (1.045 and 1.090 g/cm^3), the costs of retrofitting a hopper dredge combined with the additional weight of the plates cannot be justified at this time.

The effect of a centrifugal solids concentrator for increasing the payload of fine-grained sediments was also tested under contract. The Advanced Resource Development Corporation (ARD) conducted two series of controlled tests using a centrifugal solids concentrator device and selected sediment materials. These tests indicated that the application of a concentrator would be of some benefit. However, as noted previously, the cost of installing this device on a hopper dredge would probably be prohibitive.

The inclined plate method demonstrated the potential for significantly increasing the payload of silt-sized material in dredge hoppers. Although the application of this technique to prototype dredge hoppers may not be practical unless a lightweight version is developed, it may hold promise for other specialty applications in which solids are to be separated from a discharge stream. In some cases, environmental regulations prohibit the discharge of solids from confined disposal sites. Weight-efficient inclined plate designs can be used to clarify a continuous discharge from these sites. Specialty barges can be designed and fabricated with inclined plate configurations for

limited specialty dredging applications in which maximum solids loading is critical.

LABORATORY TESTING OF METHODS TO INCREASE HOPPER DREDGE PAYLOADS: MODEL HOPPER BIN FACILITY AND CENTRIFUGAL SOLIDS CONCENTRATOR

PART I: INTRODUCTION

Background

1. The US Army Corps of Engineers is responsible for the maintenance of over 40,000 km of inland and intracoastal waterways. One of the primary Corps responsibilities is the channel maintenance of approximately 19,000 km of the principal waterways. The annual dredging results in about 200 million cubic metres of dredged materials at a cost of over 300 million dollars. The dredging program is administered by the Corps, but the majority of the actual work is contracted to private dredging companies.

2. A variety of dredge plants are engaged in dredging operations, but the dredge of choice for open-water long disposal hauls is the hopper dredge. The hopper dredge, which is specifically designed to both dredge and haul the materials to a remote disposal site, uses a trailing suction draghead to remove sediments from the channel bottom.

3. To economize the hopper dredging process, it is a common practice to fill past overflow in an attempt to retain additional sclids in the hopper. Due to the lack of data, it is not known whether overflowing fine-grained sediments is beneficial for increasing the hopper payload. However, some of the Corps Districts do not permit overflow due to actual or perceived environmental or economic disadvantages. Under the Dredging Research Program (DRP) Work Unit, "Technology for Monitoring and Increasing Dredge Payload for Fine-Grained Sediments," devices were tested to determine their effect on increasing the payload of fine-grained dredged materials.

Objective

4. The objective of this study was to evaluate the effectiveness of selected devices and techniques for increasing the fine-grained sediment payload in dredge hoppers. Devices that attach to the end of the discharge

pipeline or are installed within the hopper bin were evaluated based on their effectiveness in separating the solids fraction of an inflowing slurry and the feasibility of prototype application. This report presents the description, methods, and results of the testing program.

Approach

5. Three types of devices were tested in a scale model hopper constructed at the US Army Engineer Waterways Experiment Station (WES). The first class of devices tested were flow diffusers, which attach to the end of the discharge pipe. These devices reduce the turbulence of flow into the hopper, creating an environment conducive to particle settling. The second class of devices tested, hydrocyclones and a solids separator, impart centrifugal forces to the inflowing slurry to separate the solids fraction. The third type of device tested was an inclined plate configuration in the hopper. The inclined plates create a density gradient within the slurry, which increases the settling rate of solids from the suspension.

Previous Work

DMRP studies

6. Within the Dredged Material Research Program (DMRP), one method studied included the use of a hydrocyclone (Tiederman and Reischman 1973). The results indicated that hydrocyclones were potentially effective in concentrating the solids fraction of dredged material slurries. However, the scale of the hydrocyclone used in those particular tests was very small, and there was no attempt to scale up for prototype application. The hydrocyclone tests performed in the WES model hopper facility (described in Part II) are larger in scale and volume of materials used.

Related DRP studies

7. Palermo and Randall (1990) conducted a Corps-wide survey on the practices and problems associated with the economic loading of hopper dredges and scows. They concluded that the practice of overflowing fine-grained sediments for the purpose of economic load gain is questionable. The particle size and settling velocities of the fine-grained materials (silt and clay size) are much lower than for sandy materials; therefore, they tend to stay in

suspension. The survey indicated that during periods of overflow conditions, much of the released slurry has the same density as that retained in the hopper itself.

Field studies of centrifugal separators

8. Field studies using centrifuge methods for dewatering river bottom sediments have proven successful. A study conducted by the consulting firm Camp, Dresser and McKee for the Florida Department of Environmental Regulation (Priede 1990) evaluated the performance of a centrifuge for dewatering contaminated river bottom sediments from the Ribault River in Jacksonville, FL.

9. The results of the study indicated that total suspended solids recovery from sediment slurries can range from 50 percent to a high of 95 percent if a polymer addition technique is used. This study not only verified the use of centrifugal separators for separating the solids fraction from dredged slurries, but also demonstrated that it was more economical to dewater the dredged sediments onsite and transport them to confined disposal sites than to haul the dredged materials off to open-water sites for disposal.

PART II: MODEL HOPPER TEST FACILITY

Facility Description

10. The scale model hopper used for the tests (Figure 1) was constructed at WES. The model, constructed of 0.64-cm-thick aluminum plate, had a capacity of approximately 0.77 m^3. The shape of the bin was similar to that of a section of an actual hopper dredge. The hopper was 0.91 m square at the top, with the bottom of the bin sloped toward the center such that the hopper depth was 0.76 m at the sides and 0.91 m at the center (Figure 2). The model hopper was suspended from an A-frame with a load cell attached to determine the weight of materials within the hopper. Two 946-ℓ mixing tanks were installed next to the model for mixing and storing a kaolinite clay or silt sediment slurry. The piping and slurry supply network consisted of 5-cm-diam polyvinyl chloride (PVC) pipe and an electric pump (Figure 3). Predetermined amounts of kaolinite or silt and water were mixed to the desired density for these controlled tests.

11. The load cell was capable of recording the hopper weight as a function of time. Density samples were taken as a vertical depth profile every 15 cm in the hopper. The overflow density was sampled by attaching a funnel to the top edge of the hopper (Figure 4). Samples of the overflow were collected in 100-ml bottles and analyzed with a digital hand-held density meter.

Materials Used in the Tests

12. The model hopper tests were conducted with both silt and clay slurries. The clay was a commercial kaolinite with a mean particle size of about 2 microns. The silt material was a naturally occurring sediment that was passed through a 200 mesh sieve to remove the sands. The naturally occurring clay fraction of the silt material was essentially removed by suspending the material in water and draining off the suspended clays. Particle size analysis was performed on the silt using standard pipette and electronic particle sizing methods. The median particle size range was 12 to 17 microns, indicating a fine to medium silt. The characteristic settling velocity was determined to be 0.020 cm/sec at a bulk wet sediment density of both 1.045 and 1.090 g/cm^3.

Figure 1. The model hopper laboratory test facility

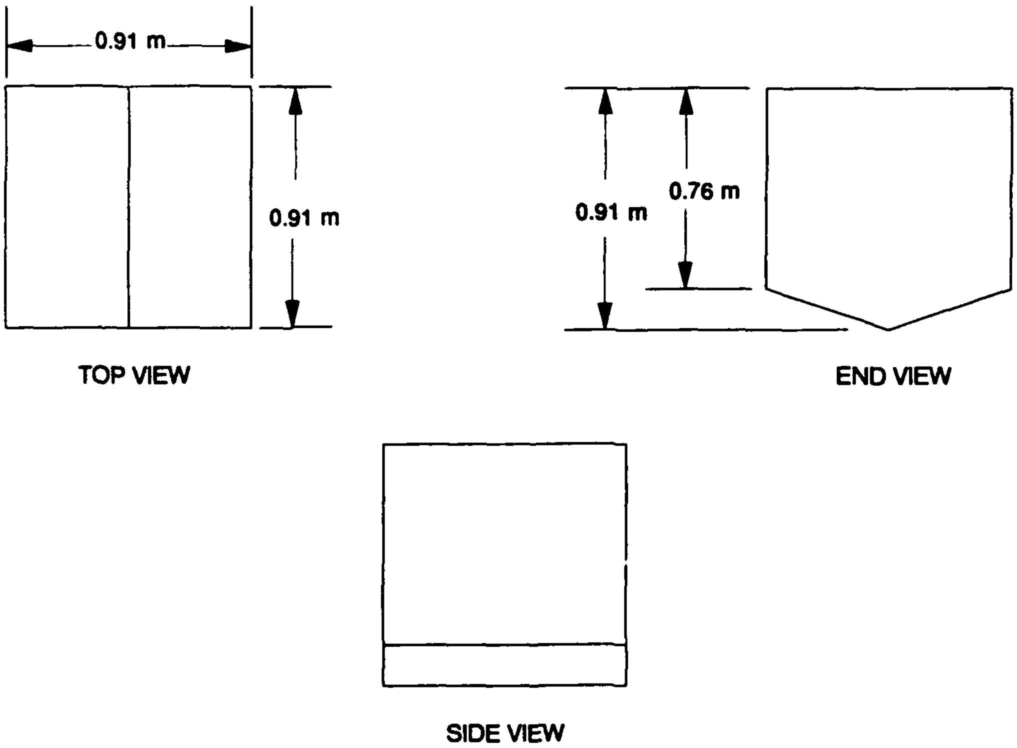


Figure 2. Model hopper dimensions

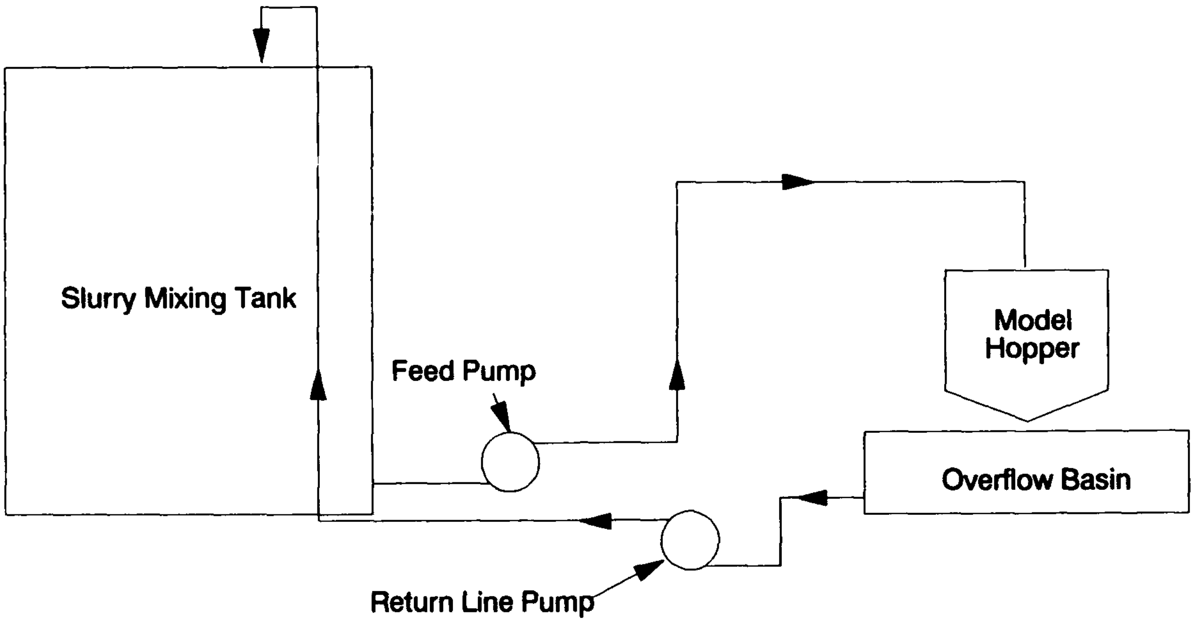


Figure 3. Model hopper overflow test loop

Figure 4. Overflow from an inclined plate test series

PART III: DIFFUSER AND HYDROCYCLONE TESTS

Diffuser Test Series

13. The initial laboratory tests were designed to determine the influence of the method of slurry discharge into the model hopper on the retention rate of fine sediments. These tests investigated the use of diffusers connected to the slurry discharge pipe. A diffuser is a device designed to evenly distribute the feed slurry into the hopper, thus reducing the turbulence within the hopper and creating a quiescent flow environment conducive to particle settling. The tests were designed so that the hopper was allowed to overflow for a specific period of time while the total hopper load was monitored.

14. A variety of diffuser designs were tested with two kaolinite clay mixtures (1.045 and 1.090 g/cm^3 density) for various inflow rates into the hopper. Kaolinite clay was used as the test medium because it represented the finest sediment size found in prototype dredge hoppers, and therefore, the most difficult to settle out of suspension. Figure 5 shows the three diffuser types tested (from left to right in the figure): a radial, vertical, and horizontal design. The test results indicated very little or no economic load

Figure 5. The diffuser designs used in the laboratory study

gain from the use of these devices for the two kaolinite clay mixtures tested. These diffusers offered no distinct advantage over conventional methods of placing slurry into hopper dredges; therefore, no further diffuser laboratory tests were conducted.

Hydrocyclone Test Series

15. A second class of devices was investigated for attachment to the discharge pipe. These devices are designed to concentrate the slurry solids before they are introduced into the hopper. They are commonly referred to as centrifugal separators or hydrocyclones. They operate on the principle of solid-liquid separation due to centrifugal forces imparted to the slurry. Figure 6 shows a typical hydrocyclone design tested in the model hopper facility. The slurry is introduced tangentially into the top portion of the conical device at a given flow rate. The conical shape of the device imparts a vortex motion to the slurry, creating significant centrifugal forces on the slurry that tend to concentrate the solid particles near the walls of the device, where they move downward and are eventually discharged at the bottom orifice as a thickened sludge. The clarified effluent is discharged as overflow through the top of the device.

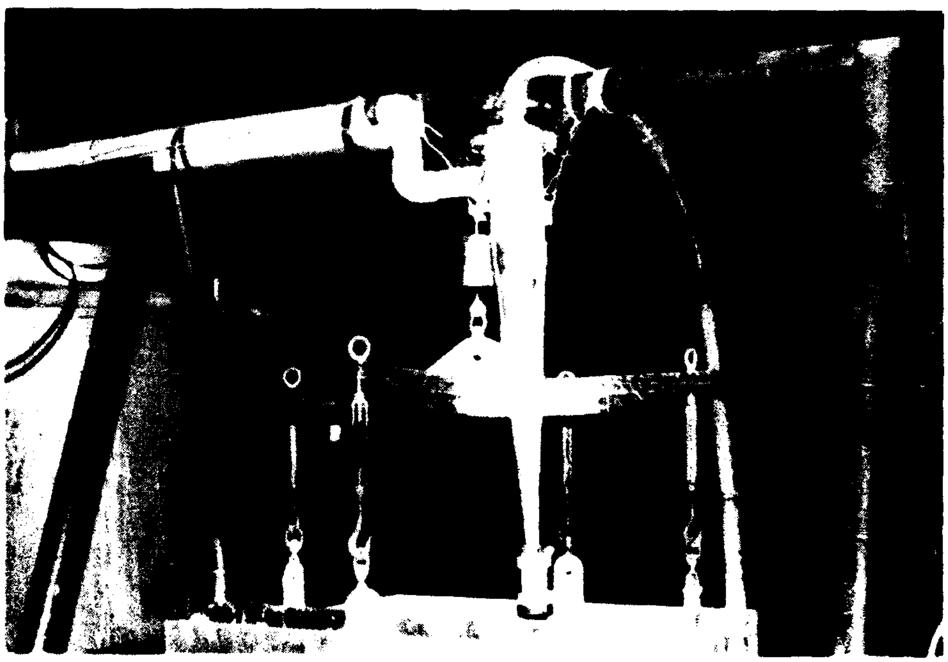


Figure 6. A hydrocyclone design being tested on the model hopper

16. The test results indicated that the hydrocyclone device was not successful in increasing the solids load in the hopper when used with a kaolinite clay suspension. Although literature suggests that hydrocyclones can efficiently separate particles within the 10- to 30-micron size range (fine to medium silts), the hardware requirements and subsequent required alterations to a working hopper dredge were not economically justifiable. Therefore, laboratory tests of the hydrocyclone centrifugal separator with a silt slurry were not conducted, and testing of the centrifugal separator was discontinued.

PART IV: MODEL HOPPER INCLINED PLATE CONFIGURATION TESTS

Background

17. Tests were conducted to investigate the effect of inclined baffle plates in a model hopper bin on the loading rate of fine-grained sediments. This settling phenomenon, referred to as the lamella or Boycott effect, accelerates the separation of suspended solids from the liquid media by creating a density gradient within the slurry. The less dense clarified liquid is then transported along the downward facing inclined plate to the surface of the hopper. As the clear water flows upward toward the surface, the higher density solids-laden water flows to the bottom of the hopper. The theory of inclined plate settlers and a description of the laboratory tests that were conducted to investigate the use of inclined plates in hopper bins to increase the settling rate of fine-grained sediments are presented in the next two sections. The test facilities and procedures are described, as well as the results.

Theory of Operation for Inclined Plate Settlers

18. One of the earliest observations of the increased settling rate of suspensions between inclined plates was reported by Boycott (1920). He observed that blood in inclined test tubes settled out at a faster rate than in vertical tubes, and that the settling rate increased with an increase in angle of inclination from the vertical axis. Other studies were conducted which qualitatively verified Boycott's observations.

19. A good qualitative description of the enhanced settling of suspensions between inclined plates was given by Zahavi and Rubin (1975). They conducted tests with a clay suspension (particle density 2.71 g/cm^3) between inclined plates. Dye was injected into the suspension between the plates and the enhanced settling phenomenon was observed. Immediately after the well-mixed suspension was placed between the plates, a clear water layer appeared under the downward facing plate. Dye injections showed that clarified liquid moved out of the suspension into this layer under the plate and flowed along the plate up to the surface.

20. Nakamura and Kuroda (1937) were among the first researchers to

present a quantitative theoretical model for settling between inclined plates. They conducted settling experiments with square test tubes inclined at 45 deg, and obtained good correlation between experimental and theoretical results.

21. Many studies have been conducted using a continuum mechanics approach to theoretically describe the inclined plate phenomenon. Of particular importance to the understanding of the inclined plate effect was the work of Acrivos and Herbolzheimer (1979). Their work verified the theoretical limitations of the inclined plate settlers and gave good insight into the design and operation of these devices.

22. The kinematic model proposed by Nakamura and Kuroda best described these qualitative observations. The enhanced settling phenomenon between two inclined plates is illustrated by Figure 7. Due to initial settling of the suspension, a clear water layer forms under the downward facing plate surface and also under the horizontal surface between the plates. The liquid flows up the plate to the surface of the settler due to buoyancy effects. Because the feed suspension has a higher density than the clarified fluid layer, a pressure gradient occurs between the layers that continually supplies a flow of clarified liquid from the feed suspension to the layer under the plate. As the clarified liquid leaves the feed suspension, a denser, solids-laden sludge

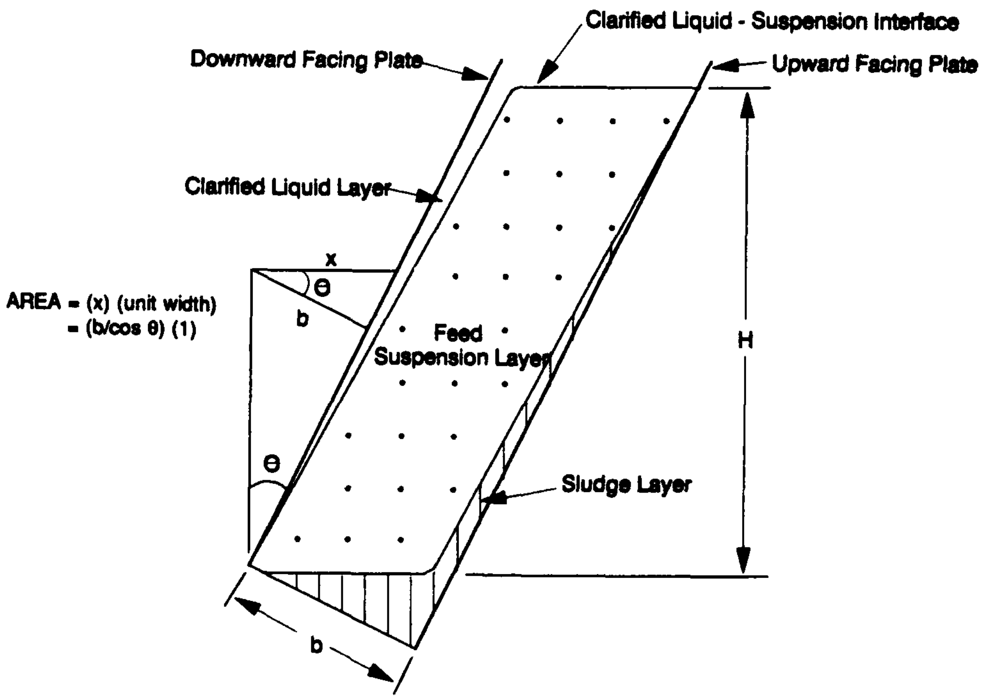


Figure 7. Region definition in the flow field between inclined plates (see paragraph 23 for definitions of terms)

layer forms on the upward-facing plate surface and slides down to the bottom of the settler.

23. Nakamura and Kuroda surmised that the increase in the settling rate of the suspension between the plates is proportional to the flow of clarified liquid from the feed suspension into the clarified liquid layer. Therefore, the total volumetric rate at which clarified liquid is formed is equal to the characteristic settling velocity of the suspension multiplied by the cross-sectional area of the vessel at the top of the suspension plus the horizontally projected area of the downward facing plate surface below the top of the suspension. Referring to Figure 7, the cross-sectional area of the vessel at the top of the suspension per unit plate width is $b/\cos\theta$. The horizontal projected area of this plate surface area per unit plate width is equal to $H \sin\theta/\cos\theta$. The total expression for the volumetric production (per unit plate width) of clarified fluid Q_1 can, therefore, be written in the form of

$$Q_1 = \frac{V_o b}{\cos\theta}\left[1 + \frac{H}{b}\sin\theta\right] \tag{1}$$

where

Q_1 = volumetric flow, cm^3/sec

V_o = characteristic settling velocity of the particles in suspension, cm/sec

b = spacing between plates, cm

θ = angle of inclination of the plate from the vertical axis, deg

H = height of the suspension, cm

The enhanced settling velocity V of the suspension between the plates can be described by the expression

$$V = V_o\left[1 + \frac{H}{b}\sin\theta\right] \tag{2}$$

From these equations, certain design criteria can be inferred. If the plate angle θ is increased, the horizontally projected plate area is increased,

thus increasing the overall settling rate. Also if the plate spacing b is decreased, the settling rate is increased.

24. The work of Acrivos and Herbolzheimer (1979) theoretically verified that Equation 2 satisfactorily predicts the settling rate between the plates provided certain criteria are satisfied. The suspension must be well dispersed and have a uniform concentration distribution. The particle Reynolds number must be small, and most importantly, the interface between the clear fluid layer and the feed suspension layer must remain stable.

25. The described inclined plate settler in the model hopper operates with countercurrent flow (Leung and Probstein 1983). For countercurrent flow, the feed slurry is input into the model hopper close to the bottom of the hopper. The feed slurry then flows up the inclined plate channel in the opposite direction to the falling sludge. The flow of the feed slurry in the opposite direction to the falling sludge creates shear stresses that act against the gravitational force pulling the sludge layer down the upward-facing plate surface. If the angle of inclination of the plate from the vertical axis is too great, the movement of the sludge layer down the upward-facing plate may become inhibited, thus reducing the efficiency of the settler.

26. Herbolzheimer (1983) investigated the stability of the boundary layer between the clarified liquid and the feed suspension. He found that the boundary layer was more stable at large angles of inclination and lower suspension concentrations. At small plate angles (<30 deg), waves began to form at the interface of the clear liquid and feed suspension that, upon breaking, caused some entrainment of sediment into the clarified liquid stream, thus reducing the efficiency of the settler.

Model Hopper Test Configuration

27. The model hopper was fitted with a slotted carriage for holding the inclined plates (Figures 8 and 9). The lengths of the plates were varied to accommodate the horizontal diffuser that was used to input the slurry into the hopper. The plate lengths varied from 15 cm to 71 cm, with the longest plates located in the back of the hopper, away from the diffuser.

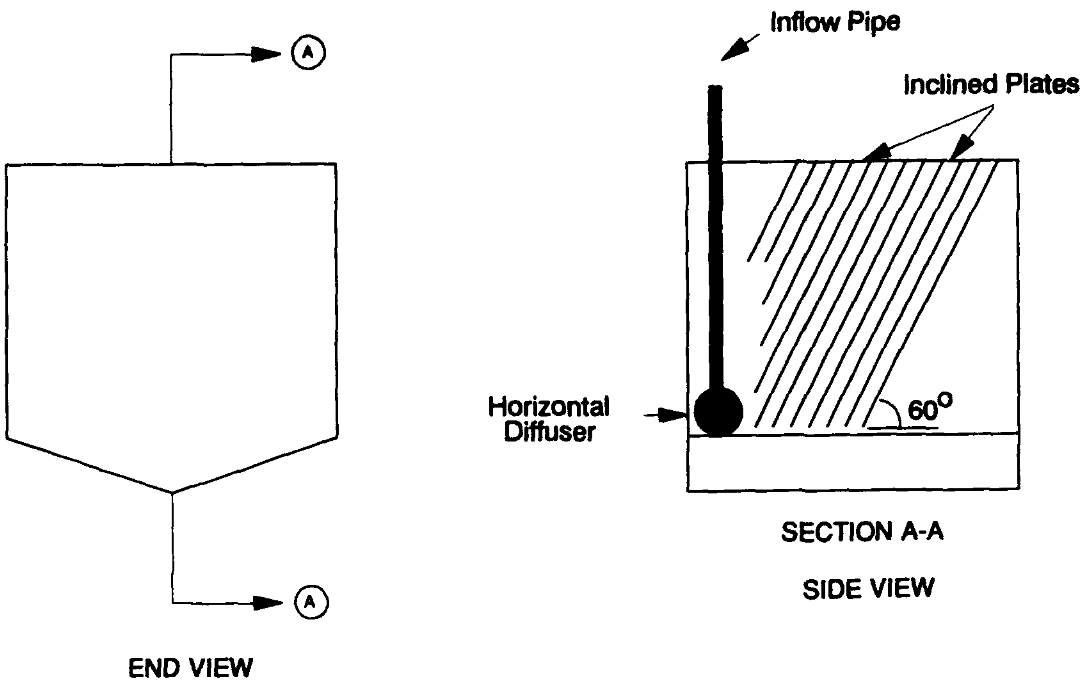


Figure 8. Approximate plate configuration in the model hopper, section view

Figure 9. Inclined plate arrangement in the model hopper

Test Results and Discussion

Clay slurry tests

28. To investigate the effects of inclined plates on the settling rate of a clay slurry, six inclined plates were placed in the model hopper (Figure 10a). The plates were inclined 30 deg from the vertical, with 10-cm spacings between the plates. The plates were 71 cm long. Overflow tests were conducted at hopper fill rates of about 0.064 to 1.0 cm/sec. The hopper fill rate is the rate at which the slurry rises vertically in the hopper. This rate is calculated by the following equation

$$V_{fill} = \frac{Q_i}{A_h} \tag{3}$$

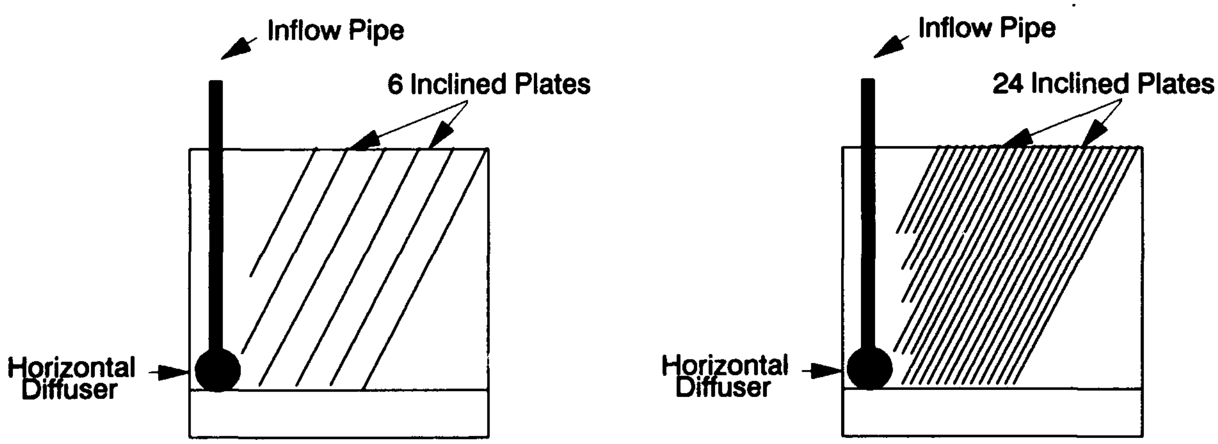
where

V_{fill} = vertical fill rate, cm/sec

Q_i = discharge into the hopper, cm^3/sec

A_h = cross-sectional area of the hopper, cm^2

Although the load cell was not sensitive enough to indicate any load gain in the hopper, a visual inspection of the overflow indicated that liquid-solid separation was taking place.



a. Six inclined plates

b. Twenty-four inclined plates

Figure 10. Side view of plate configurations in the model hopper for the clay slurry tests

29. Further tests were conducted with 24 inclined plates in the hopper (Figure 10b). This plate arrangement resulted in a spacing of one plate per 2.54 cm. Vertical profile density samples taken during these tests indicated that at the low hopper fill rate (0.064 cm/sec), up to 15 percent of the feed solids were being retained in the hopper during overflow. At a higher, more practical range of fill rates, around 0.25-1.0 cm/sec, the density samples indicated that no feed solids were accumulating in the hopper.

30. The data from the load cell were erratic during these initial tests. The stated accuracy of the load cell is 1 percent of full scale, or ±9 kg for these test purposes. It was decided that because of the insensitivity of the load cell, only the density of the hopper overflow would be sampled in subsequent tests. By recording the density of the overflow as a function of time, a mass balance was performed on the hopper to determine the amount of feed solids retained during overflow.

Mass balance calculations

31. Assuming that the flow rate into the hopper is the same as the overflow rate, the mass retained in the hopper per unit time $M(t)$ in grams is

$$M(t) = \left[\frac{BWD_f - BWD_o}{d_m - d_w}\right] \times d_m \times Q \qquad (4)$$

where

BWD_f, BWD_o - bulk wet density of the feed and overflow respectively, g/cm^3

d_m - density of silt, g/cm^3

d_w - density of the water, g/cm^3

Q - volumetric flow rate, cm^3/sec

The data were analyzed for an overflow time of 200 sec. The total feed solids mass M_t available to the hopper during the 200-sec overflow period would therefore be

$$M_t = M(t) \times \left[\frac{BWD_f - d_w}{BWD_f - BWD_o}\right] \times 200 \qquad (5)$$

The efficiency of the inclined plates in settling out the solids in suspension was determined by calculating the percent of feed solids retained in the hopper during overflow. This percent is the feed solids mass retained in the hopper divided by the total feed solids mass input into the hopper during the overflow period. The feed solids mass retained was calculated by incrementally summing the overflow density versus time data generated from the laboratory tests (Figure 11). For overflow density samples d_o, d_1, $d_2 \ldots d_n$ (with d_n the density of the last sample) taken at times t_o, t_1, $t_2 \ldots t_n$ (with t_n equal to 200 sec, the time of the last sample taken), the average overflow bulk wet density per sample interval is

$$BWD_{oavg} = \frac{BWD_{oi+1} + BWD_{oi}}{2} \tag{6}$$

with $i = 0, 1, 2 \ldots n-1$. The total feed solids retained during the overflow cycle M_r would then be described by

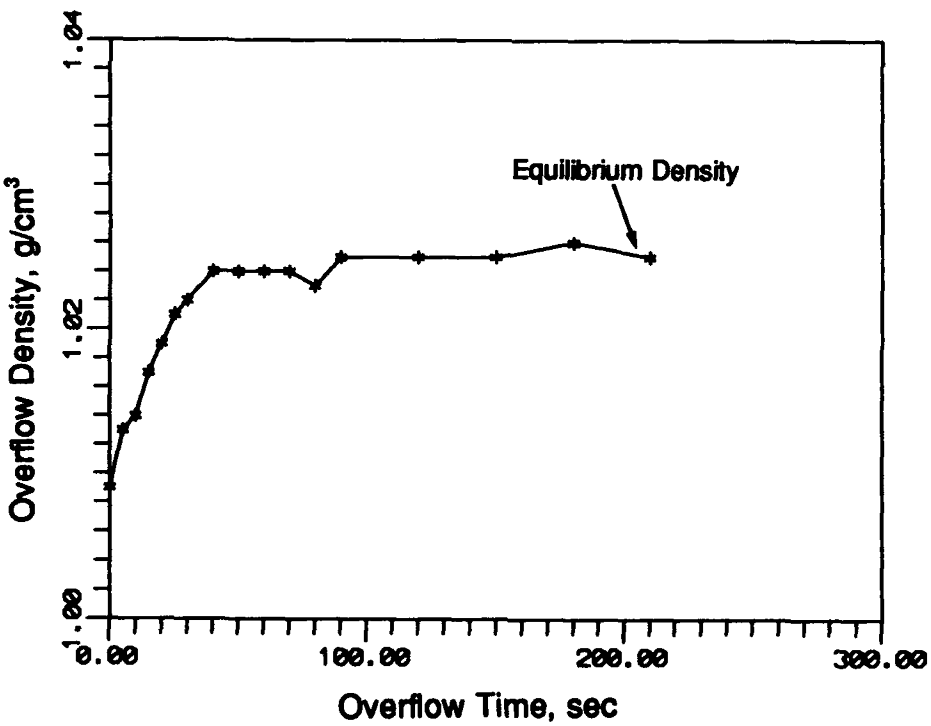


Figure 11. Typical data record of overflow density as a function of overflow time, 1.045-g/cm³ feed density

$$M_r = \sum_{i=0}^{n-1} \left[\left(\frac{BWD_f - BWD_{oavg}}{d_s - d_w} \right) \times d_s \times Q \times (t_{i+1} - t_i) \right] \quad (7)$$

This equation represents the total inflow solids mass accumulated in the hopper over a 200-sec overflow cycle. The percentage of retained solids P_r in the hopper would therefore be calculated by

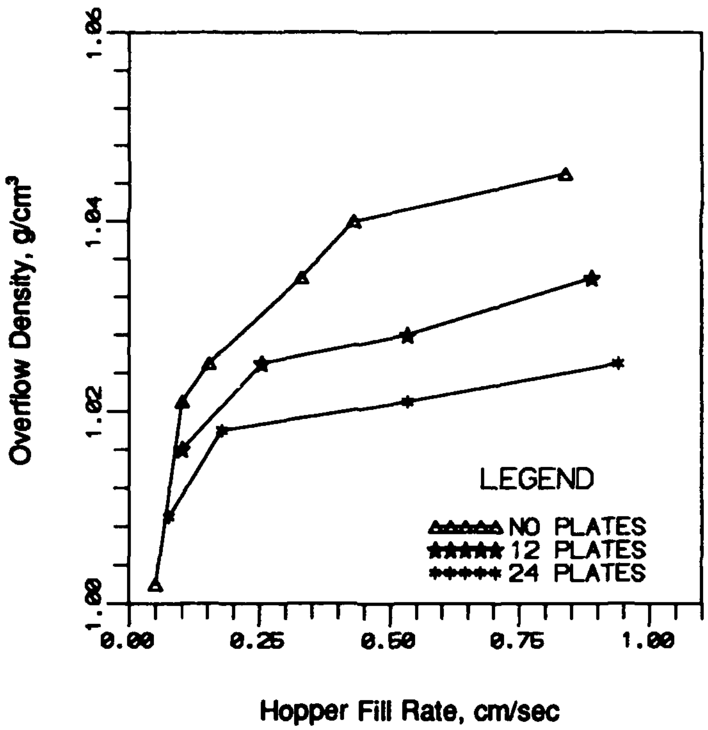
$$P_r = \frac{M_r}{M_t} \times 100 \quad (8)$$

Silt slurry tests

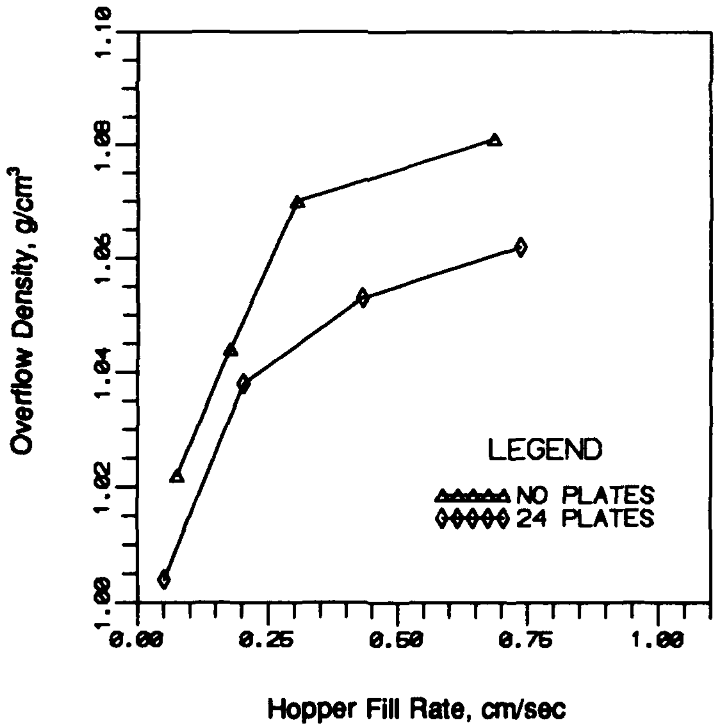
32. Silt slurry tests were conducted with and without plates in the model hopper. Tests were conducted without plates for baseline data on the settling rate of the suspended sediments due to the effect of gravity. Tests were conducted for both 24- and 12-plate arrangements. The 24-plate arrangement had a plate spacing of 2.54 cm, while the 12-plate arrangement had a plate spacing of 5.08 cm. The hopper fill rates were varied within the range of about 0.064–1.0 cm/sec. The overflow was sampled between the 71-cm-length plates located in the back of the hopper. The following test description and results are based on flow through the 71-cm plates.

33. Figures 12 and 13 describe the results of the silt slurry overflow tests. Tests were conducted at slurry densities of 1.045 and 1.090 g/cm^3 to determine the effect of concentration on plate performance. Figure 12 shows the density of the overflow at equilibrium as a function of hopper fill rate for both the baseline conditions of no plates in the hopper and conditions of 12 and 24 plates in the hopper. The density of the overflow at equilibrium is the density reached after a model hopper overflow duration of 200 sec (Figure 11). Only the 24-plate arrangement was tested with the 1.090-g/cm^3 density slurry. Figure 13 shows the percent of solids retained in the hopper as a function of the hopper fill rate. These plots were also generated for a 200-sec model hopper overflow time.

34. Figure 12 clearly shows that the plates are effective in lowering the overflow density, thus increasing the solids retained in the hopper. This figure indicates that the efficiency of the plates increases with hopper fill

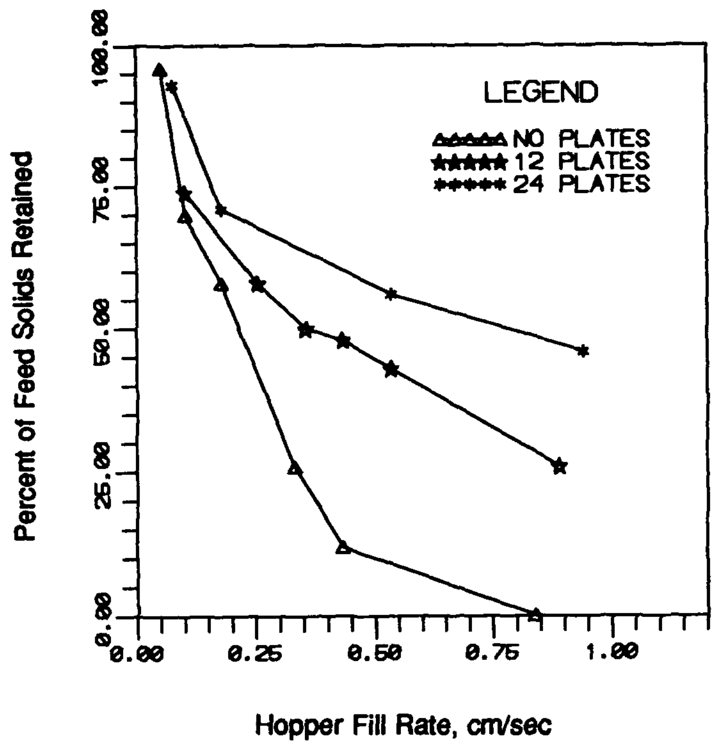


a. 1.045-g/cm³ feed density

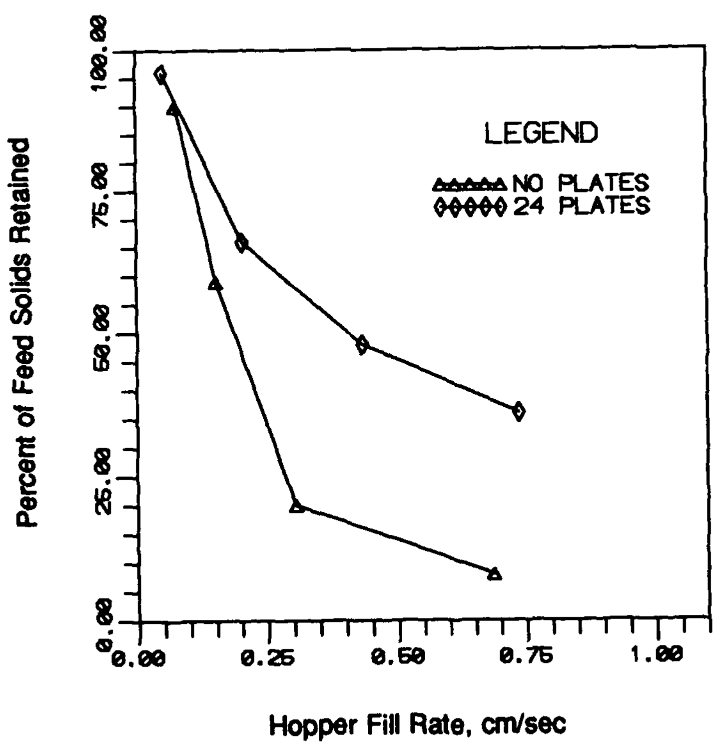


b. 1.09-g/cm³ feed density

Figure 12. Overflow density at equilibrium for a 200-sec overflow duration



a. 1.045-g/cm^3 feed density



b. 1.09-g/cm^3 feed density

Figure 13. Percent of feed solids retained for a 200-sec overflow duration

rates greater than 0.25 cm/sec, becoming constant at about 0.50 cm/sec. This efficiency is defined by the change in density that occurs between the curves representing conditions of no plates and 24 or 12 plates in the hopper. The plots of percent solids retained as a function of hopper fill rate (Figure 13) indicate that, for the 1.045-g/cm^3 feed density, the 24-plate arrangement with 2.54-cm plate spacings resulted in 50 percent more feed solids retained than for the case of no plates in the hopper. The 12-plate arrangement with 5.08-cm plate spacings resulted in about 25 percent more feed solids retained. This percentage increase was constant for hopper fill rates of about 0.50 to 1.0 cm/sec. With an increase in feed density to 1.09 g/cm^3, the 24-plate arrangement resulted in about a 30 percent increase in feed solids retained in the hopper. This percentage increase was constant for hopper fill rates of about 0.50 to 0.80 cm/sec.

35. These results are based on all of the slurry passing between the plates with the maximum length of 71 cm. In prototype applications, a portion of the flow would not pass between plates because of space limitations in the hopper. This would result in a somewhat reduced solids retention efficiency in the hopper.

36. The inclined plates in the model hopper occupied only a small portion of the available volume, but added substantial weight to the hopper. For a practical application, it would be necessary to fabricate the plates out of low-density plastics or composite materials, such as graphite-epoxy, that possess the material strength and abrasion resistance to survive in a dredge hopper environment.

37. By increasing the solids content of the slurry by a factor of two, the percent of feed solids retained in the hopper was reduced from 50 to 30 percent. Because of this decrease in plate efficiency with increasing concentration, the inclined plate concept with this configuration may be viable only for low-density slurries (< 1.1 g/cm^3).

Dimensional Scaling of the Inclined Plate Settler

38. The equation for describing the volumetric production of clarified fluid due to the presence of inclined plates was earlier derived as Equation 1:

$$Q_1 = \frac{V_o b}{\cos \theta} \left[1 + \frac{H}{b} \sin \theta\right] \qquad \text{(1 bis)}$$

The enhanced settling velocity due to the plates was defined as Equation 2:

$$V = V_o \left[1 + \frac{H}{b} \sin \theta\right] \qquad \text{(2 bis)}$$

Assuming the settling rate due to gravity is the same in the prototype and the model, and the production of clear water flow under the plate scales per unit plate area, the increase in the settling velocity beyond the characteristic settling rate of the suspension is proportional to the relationship:

$$V \propto \frac{H}{b} \sin \theta \qquad (9)$$

Therefore, the settling rate can be increased by increasing the aspect ratio of the suspension height divided by the plate spacing for a given angle of inclination.

39. Using the relationship in Equation 9, the model hopper results can be approximately scaled to a prototype hopper of given dimensions. For the model hopper tests, 71-cm plates were used in the hopper. The suspension height for a 30-deg plate inclination angle is equal to 71 × cos 30 or 61.5 cm. The smallest plate spacing used in the tests was 2.54 cm. Therefore, the prototype suspension height and plate spacing will scale to the relationship

$$\frac{\text{Suspension Height}}{\text{Plate Spacing}} = \frac{61.5}{2.54} = 24.2 \qquad (10)$$

For example, for a prototype hopper with dimensions of 12-m depth and 12-m width, a 10-m suspension height between the plates may be required.

Therefore, the corresponding plate spacing for the hopper would be 10/24.2 or 0.41 m. The plate length for a 30-deg angle of inclination from the vertical would be 10/cos 30 or 11.5 m.

40. This relationship should serve only as an approximation for initial settler design. It was apparent from the test results that the interface between the clarified layer and the feed suspension layer was not stable, with sediment entrained into the clear water layer.

41. The inclined plate settler tests were performed under dynamic flow conditions, with a steady flow of slurry into the hopper. The rate at which the slurry rises in the hopper will directly influence the settling rate of fine-grained sediments in the suspension. In prototype dredge hoppers, the rate at which the slurry rises in the hopper can range from 0.60 to 1.0 cm/sec. The combination of the drag and buoyancy forces exerted on the fine sediment particles from the upward flow of the slurry at these rates is sufficient to negate particle settlement, and subsequently cause the sediments to leave the hopper with the overflow.

42. For example, consider an ideal hopper environment with a laminar flow field containing idealized spherical sediments that settle as the hopper fills at a given rate. The ability of the sediments to settle in this environment can be estimated by performing a force balance on the sediment particle. The sum of the forces acting on the particle is described by

$$\sum F = F_w - F_b - F_d \tag{11}$$

where

F_w = force due to the weight of the sediment particle (gravity)

F_b = buoyancy force (weight of fluid displaced by the particle volume)

F_d = drag force (viscous effects) acting on the particle

For the case of hopper fill rates within the range of 0.60 to 1.0 cm/sec, the particle Reynolds number would be less than 1; therefore this would be described as creeping flow, or flow in which the flow about the particle is completely viscous. For this type of flow, the friction drag is given by Stokes law as

$$F_d = 3\pi\mu VD \tag{12}$$

where

μ = dynamic viscosity of the fluid

V = velocity of the flow around the spherical sediment particle

D = particle diameter

A force balance performed on idealized spherical sediments in the size range of 2 microns (clay), 17 microns (fine silt), and 60 microns (coarse silt-fine sand) indicated that only sediments with particle sizes greater than approximately 60 microns (coarse silts and sands) have sufficient mass to overcome the drag and buoyancy forces opposing the particle fall in prototype hoppers at typical hopper fill rates of 0.60 to 1.0 cm/sec.

43. The equations presented in paragraph 23 for predicting the enhanced settling velocity of suspended sediments between inclined plates were derived for static conditions. For dynamic flow conditions into the hopper, the enhanced settling velocity would be somewhat less, due to the effects described in paragraph 42. Considering the equation derived earlier for the enhanced settling velocity, with model hopper test conditions of 0.020-cm/sec settling velocity, 61.5-cm suspension height, 2.54-cm plate spacing (24-plate arrangement), and 30-deg plate angle, this equation yields an enhanced settling velocity of 0.26 cm/sec. Therefore, under the ideal condition of a perfectly stable interface between the clarified liquid layer and the feed suspension layer, and static conditions in the hopper, the equilibrium overflow density for the model hopper should be that of clarified liquid (water) up to a hopper fill rate of 0.26 cm/sec. The data resulting from the dynamic model hopper tests (Figure 12) indicate that sediment is entrained into the clarified liquid layer at lower flow rates, reflecting the instability of the boundary layer and the viscous drag effects of the slurry rising in the hopper.

44. Laboratory tests confirmed that the characteristic particle fall velocities in both the 1.045- and 1.090-g/cm^3 density slurries were almost identical (0.020 cm/sec), indicating that the reduction in settler efficiency with an increase of suspension concentration was probably due to an increased instability of the boundary layer between the clarified liquid and the feed suspension. The boundary layer stability studies performed by Herbolzheimer (1983) indicated that an increase in suspension concentration as well as a

small plate angle resulted in wave formation and mixing in the boundary layer. Because of the countercurrent operation of the model hopper inclined plate settler, the maximum allowable angle of inclination of the plates was 30 deg from the vertical axis. This may prove to be a major limitation for an inclined plate settler design in dredge hoppers operating in a countercurrent mode.

Analysis and Discussion of Test Results

45. The following points are based on the inclined plate test results:

a. For clay suspensions, an inclined plate spacing of one plate per 2.54 cm in the hopper increased the percent of feed solids retained in the hopper by only about 15 percent at an impractically low hopper fill rate of 0.064 cm/sec.

b. Test results indicated that the overall efficiency of the inclined plates decreased with increased slurry density, increased with decreased plate separation, and increased with decreased flow rate.

c. The plates were more efficient at the higher hopper fill rates (> 0.25 cm/sec) for the silt slurry than for the clay slurry.

d. For hopper fill rates in the range of 0.25 to 1.0 cm/sec with a 1.045-g/cm^3 silt slurry and an inclined plate spacing of one plate per 2.54 cm, 50 percent more feed solids were retained than when no plates were present in the hopper. By doubling the plate spacing to 5.08 cm, the percent solids mass retained dropped to about 25 percent, or approximately one-half.

e. When the silt slurry density was increased from 1.045 to 1.090 g/cm^3, a 20 percent reduction in the solids retained in the hopper occurred over a 200-sec overflow time for a plate spacing of one plate per 2.54 cm in the hopper.

f. At the one plate per 2.54-cm spacing, the plates occupied very little volume, but the total weight added to the hopper was substantial.

46. The model hopper tests confirmed that the inclined plate settler technique may be viable for suspended sediments within the silt size range. The implementation of inclined plates in dredge hoppers is constrained not only by the type of sediments dredged, but also by the available volume in the hopper for insertion of the inclined plates. Most hoppers have numerous obstructions that would limit the size and number of plates that could be installed.

47. The equation presented for the prediction of enhanced settling

velocity in inclined plate settlers serves as a good guideline for the initial design of an inclined plate arrangement for dredge hoppers or other specialized applications. The model hopper experiments confirmed that settler efficiency is directly related to the ratio of the suspension height to the inclined plate spacing.

48. The laboratory tests described were not designed solely to predict the performance of plate settlers in prototype applications, but more importantly, to verify that the design equations can serve as an approximate guide for developing a prototype dredge hopper plate settler. Further tests should be conducted with model plate settlers that operate in a continuous batch settling mode. This would involve much longer overflow times than the 200-sec duration used in these tests. These tests would provide data on the long duration overflow efficiency of the plate settler and give a better idea of the practicality of the use of plate settlers for prototype dredge hopper applications.

49. Although metal inclined plates installed in a prototype dredge hopper would add substantial weight to the dredge, low-density, high-strength plates fabricated from composite materials could reduce the unit weight by over 50 percent. Further studies of plate boundary layer behavior should be undertaken to further increase the efficiency of the settler.

PART V: CENTRIFUGAL SOLIDS CONCENTRATOR STUDY

Background

50. This part of the study to increase dredge hopper payload was conducted by the Advanced Resource Development Corporation (ARD), Columbia, MD. ARD has been working independently for the last several years developing and applying a solids concentrator for sludge removal operations. The sludge removal concept involves the periodic removal of solids accumulated within tanks or sumps at industrial facilities using a portable separator system. This system has been previously tested using high-loading coarse fractions similar to sand. Low-loading fractions such as silt and clay have not been tested. The purpose of these tests was to apply this concept to the concentration of fine-grained dredged material.

Theory of Testing Program and Approach

51. The solids concentrator operates by passing a feed stream of slurry through a series of baffles or slots within a chamber. The baffles impart a vortex motion to the slurry and accelerate the heavier fractions of the sediment slurry to the outside of the vortex. These heavier fractions form a concentrated sludge and are removed in the underflow while the remaining effluent, containing less sediment, flows out as the overflow. The solids concentrator works in principle much like the hydrocyclone devices discussed in a previous section of this report.

52. Two series of tests were conducted. Small-scale testing was performed to determine solids concentration performance at both small-scale and low flow rates (38-57 ℓ per minute). Large-scale testing was performed to determine solids concentration performance at a larger scale and higher flow rates (757-1,514 ℓ per minute) with correspondingly larger equipment of similar design. Sediment mixtures were predetermined and used in both series of tests for comparison.

Materials Used in the Tests

53. The materials for the tests were carefully selected to represent

sediments encountered during the dredging of fine-grained sediments. Actual field samples were not desirable because of the cost involved in obtaining them and the nonrepeatability of tests when using them. The desired mixture was not commercially available and therefore was prepared onsite by the contractor.

54. Three materials were mixed in various concentrations for use in the tests. Two types of silica sand and a very fine clay material were used. The sand materials were Berkeley sand (85 percent passing No. 325 sieve) and Gore sand (93 percent between No. 100 and No. 30 sieves). The clay material is commercially known as Red Art Clay and has a high illite content. The mixture desired for the tests was 12.5 percent solids by weight and included 0.25 percent salt. The three mixtures used in the tests are given in the following tabulation:

Test Sediment	Percent Gore Sand	Percent Berkeley Sand	Percent Red Art Clay
A	20	0	80
B	20	20	60
C	20	60	20

Small-Scale Tests

55. These tests were of the batch type, with a premixed sediment processed in a predetermined time. Initial small-scale tests determined the minimum concentrator flow rates required to pick up the sediments from the bottom of the test tank and entrain them into the inflow stream. The established test flow rates used were 37 and 42 ℓ per minute.

56. The approximate test configuration is diagrammed in Figure 14. The solids content of the slurry accounted for 12.5 percent of the mixed slurry by weight, and was distributed evenly across the bottom of the tank. The mixture was allowed to settle for a period of not less than 30 days to ensure a settled test bed. After this waiting period, the small-scale tests were begun. The equipment was operated for 3 min with samples collected every 2 min. The mixture criteria and data gathered from the small-scale tests were used to establish the methods and testing procedures for the large-scale test.

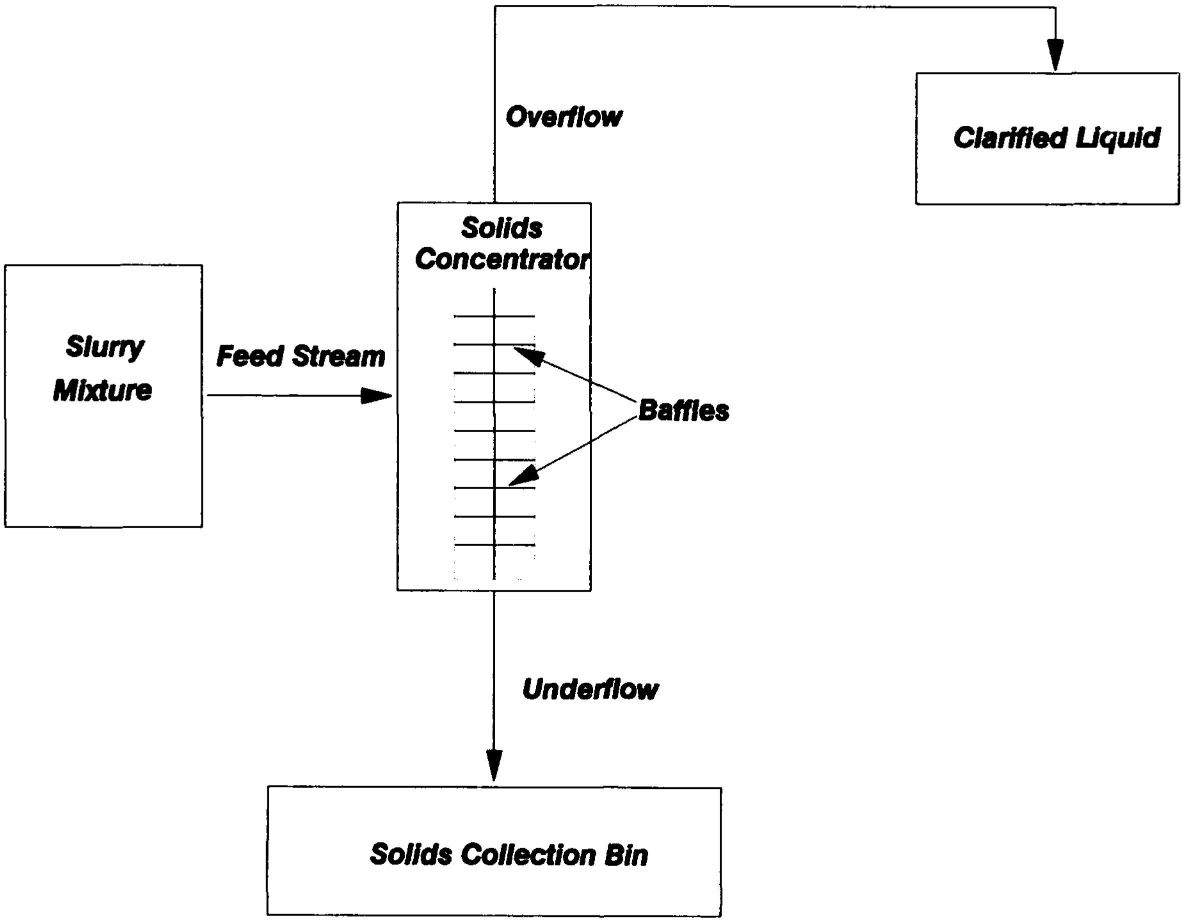


Figure 14. Solids concentrator test configuration

Large-Scale Tests

57. The final phase of testing employed much larger quantities of slurry and a much larger capacity solids concentrator. Test sediment material A was used (paragraph 54). The large-scale test configuration was very similar to the previous configuration used for the small-scale tests with the exception of scale (flow rates were increased by 20 to 40 times).

58. The system used for the large-scale tests was a commercially available solids separation unit normally used for separating solids from process waste streams at manufacturing plants or from irrigation systems (Figure 15). The two-stage system operated at flow rates of 757, 1,136, and 1,514 ℓ per minute, compared to a large hopper dredge that may have pumping rates on the order of 113,562 ℓ per minute. The unit was rated to remove over 98 percent by weight of sand-sized solids from the slurry stream. A more complete

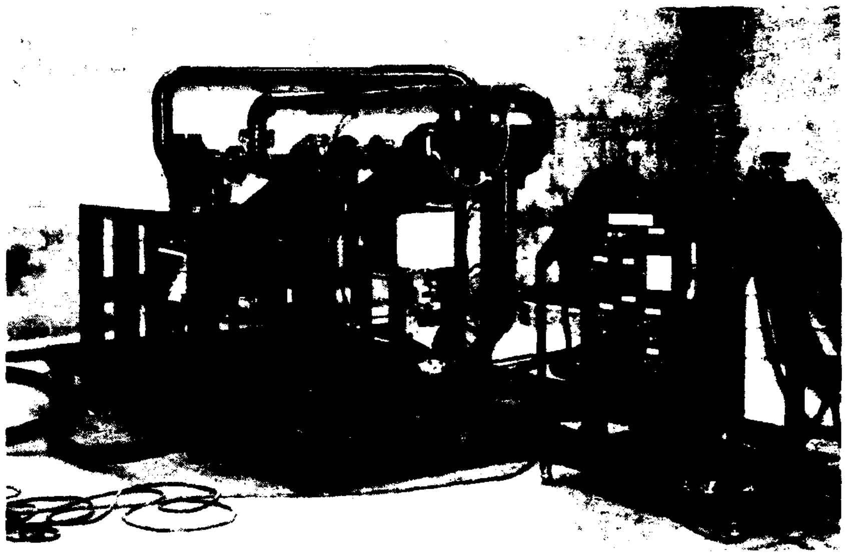


Figure 15. The ARD solids concentrator setup

description of the equipment is contained in Silverman, Thomas, and Strem.*

Test Results and Discussion

59. There were no distinct differences in the test results between the three types of sediments (A, B, and C) in the small-scale tests; therefore, only sediment A was used in the large-scale tests.

60. Several parameters were devised to evaluate test results and rate the performance of the concentrator. Only one of the parameters, concentration index (CI), will be described and summarized here. The concentration index is defined as

$$CI = \left(\frac{\text{underflow concentration by weight}}{\text{feed concentration by weight}} - 1 \right) \times 100 \qquad (13)$$

The test results, along with the concentration index, are presented in Table 1.

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* E. B. Silverman, M. Thomas, and R. Strem. 1989 (Dec). "Fine-Grained Sediment Separation Using A High Efficiency Solids Concentrator," prepared for US Army Engineer Waterways Experiment Station, Vicksburg, MS, under Contract Number DACW39-89-C-0018, by the Advanced Resource Development Corporation, Columbia, MD.

61. The volume of material passing through the underflow was also varied during both the small- and large-scale tests. An expected inverse trend between the volume fraction passing through the underflow and the concentration index was confirmed. This is depicted graphically in Figure 16 where all of the data are combined for the two test series.

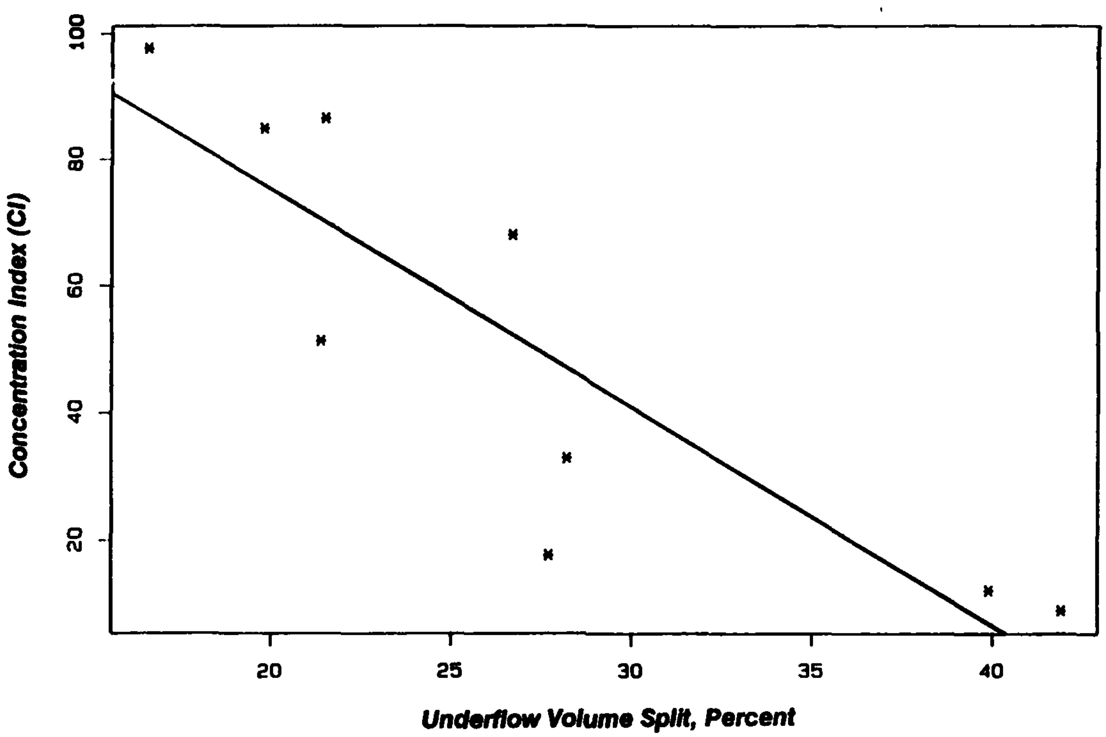

Figure 16. Volume versus concentration index trend

62. Several of the small-scale tests reached concentration indexes of 85 to 98 percent at low underflow volumes, thereby almost doubling the load in the underflow. The concentration index appears to have improved with increased flow rate in the large-scale tests (i.e., 8.8 percent at 757 ℓ per minute and 68 percent at 1,514 ℓ per minute). It also appears that the experimental techniques improved during the large-scale tests. However, problems were noted at the slurry intake during this test series. The 1,514-ℓ per minute test had an impressive concentration index (68 percent), which is almost as great as attained in the small-scale tests. The concentrators were apparently operating at the upper end of the flow range during the large-scale tests.

63. The results of these controlled and relatively small scale tests indicated that a solids concentrator would be limited in its effectiveness in

the dredging of relatively fine grained sediments. The potential benefits of large-scale field testing of the solids concentrator under simulated dredging conditions were evaluated. The evaluation concluded that the increased weight of the dredge when fitted with the solids concentrator device would not be cost effective. However, the technique may prove to be a useful tool in small-scale operations such as the cleanup of small harbors or the removal of subaqueous hazardous material from contaminated sites. It appears that the concentrator method could also be beneficial in confined disposal operations where concentration of the sediments would reduce the required site volume.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

64. Laboratory testing has indicated that the inclined plate concept and the centrifugal solids concentrator techniques for increasing solids retention in the dredging of fine-grained sediments have limited potential for prototype hopper dredge application.

65. The following conclusions are based on the results of controlled tests performed at the WES model hopper bin facility and with the centrifugal solids concentrator by the ARD Corporation:

a. Hydrocyclones and diffuser configurations did not indicate any significant increase in fine-grained solids retention.

b. The inclined plate concept tests provided initial design parameters for developing large-scale inclined plate settlers.

c. The centrifugal solids concentrator tests performed by the ARD Corporation indicated a limited usefulness in removing fine-grained materials from a slurry.

d. Although these initial laboratory evaluations suggest that the methods tested are not presently economically justifiable when considering the additional weight and the extent of modifications required to retrofit an existing hopper dredge, advances in the design and operation of the inclined plate settler and solids concentrator may lead to cost-efficient prototype applications.

Recommendations

66. The inclined plate concept and the centrifugal solids concentrator techniques may be applicable to upland disposal operations, which require that suspended solids be removed from confined disposal site effluent. The use of inclined plates in settling basins would reduce the settling basin surface area requirement, resulting in a more space-efficient batch settling operation. The fabrication of inclined plates with low-density, high-strength composite materials can reduce the unit weight by 50 percent over a conventional metal design. Advances in boundary layer studies of the inclined plate effect could result in even higher efficiencies than reported in this publication. More research and testing are needed to further define the optimum operating conditions of these devices and other beneficial applications in the areas of contaminated material removal from disposal site effluent. With this

type of installation, the size and weight factors would not be as critical as they exist on an operational hopper dredge. Tandem designs using a solids concentrator device in series with an inclined plate settling basin may be the most effective method for removing a high percentage of suspended materials in the effluent.

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Table 1

Summary of Test Results

Test Series	Flow Rate ℓ/min	Sediment Mixture	Concentration Percent Solids by Weight Feed	Overflow	Underflow	CI percent
Small	37	A	12.5	8.9	16.6	32.8
	37	B	12.5	6.5	14.0	12.0
	37	C	12.5	8.0	23.1	84.8
Small	42	A	12.5	7.1	23.3	86.4
	42	B	12.5	7.7	24.7	97.6
	42	C	12.5	8.3	18.9	51.2
Large	757	A	12.5	NA*	13.6	8.8
	1,136	A	12.5	NA	14.7	17.6
	1,514	A	12.5	NA	21.0	68.0

* NA - not available.

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